

Critical Review of the Procedures Used for Estimation of the Energy Content of Diets and Ingredients in Poultry

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Primary Audience: Feed mill managers, Nutritionists, Poultry technicians, Researchers

SUMMARY

The energy content of ingredients is estimated from tabulated values, predictive equations, and in vivo bioassays. Numerous institutions and research centers have edited comprehensive tables to evaluate the nutritive value of ingredients in poultry diets. However, the energy values provided in these tables vary widely for most traditional raw materials, including protein meals, cereals, and lipid sources. Various reasons help to explain some of the discrepancies among sources but in most cases, the differences in energy reported are not justified. Predictive equations based on near-infrared reflectance (NIRS) technology are gaining popularity for energy estimation of dietary ingredients. Online regression equations facilitate feed formulation but often the equations available are not suitable for use under many practical conditions. In vivo trials conducted at research institutions and feed companies are valid sources of information, especially for non-traditional ingredients. However, in vivo tests are of limited use under most practical conditions. In summary, each of the methods described has advantages and disadvantages. Two priorities in poultry research are the standardization of the procedures used in the in vivo trials and the online implementation of simple methods, based on NIRS technology, to predict accurately the energy content of ingredients and feeds. Nutritionists and feed mill managers should be aware of the methodology used and their applicability before selecting any of the procedures reported in this review.

Key words: energy evaluation, in vivo bioassays, metabolizable energy, predictive equations, tabulated energy values

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ABBREVIATIONS

AA: amino acids
ANF: anti-nutritional factor
DDGS: dried distillers grain
FFSB: fullfat soybeans
GE: gross energy

GIT: gastrointestinal tract
HP: heat processing
N: nitrogen
NE: net energy
NFE: nitrogen free extract
NIRS: near-infrared reflectance
NSP: non-starch polysaccharide
RSM: rapeseed meal
SBM: soybean meal

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SFM: partially decorticated sunflower meal
TI: trypsin inhibitors

DESCRIPTION OF PROBLEM

Dietary energy represents a major cost in poultry feeds. Tabulated values, predictive equations, and in vivo tests are used by the industry to estimate the energy content of diets and ingredients. In practice, table values are the basis of feed formulation under most practical situations. However, the wide variability among research institutions on the energy value of many ingredients limits their applicability. In recent years, predictive equations based on data obtained by near-infrared reflectance (NIRS) technology, wet chemistry, or in vitro and in vivo tests have gained interest and have resulted in improved formulation accuracy and reduction of safety margins and diet cost. In vivo bioassays conducted at universities and research institutes provide abundant scientific information on the nutritive value of ingredients but are of limited use under practical field conditions. In all cases, values reported show a high variability. Research is needed on the influence of factors difficult to control, such as bioassay methodology, bird type, diet composition, ingredient processing, and fiber, protein, and fat content of the feeds, on energy utilization. Consequently, it is not possible to make a fair recommendation on which procedure is best.

INTRODUCTION

Accurate estimation of the nutritive value of ingredients is fundamental to reduce feed cost [1]. The AME system is widely used in the evaluation of the energy content of ingredients and diets [2–4], but the system is not accurate under all circumstances [5, 6]. For comparative purpose, the AME content of ingredients and diets is usually corrected for nitrogen (N) retention (AMEn). The N correction has a greater effect on the energy content of high-protein ingredients, such as soybean meal (SBM), than on that of low protein ingredients, such as cereals [7]. In this respect, Lopez and Leeson [8] reported that the correction for N of the energy content of ingredients imposed a penalty of 3%–5% to

corn but of 7%–12% to SBM. Similarly, correction for N reduces the energy content of high CP diets more than it does for low CP diets [8]. Consequently, AMEn values might penalize the real contribution of protein sources to the energy of the diet, especially in modern birds fed diets formulated on ileal digestible amino acids (AA) and ideal protein basis, in which a high proportion of the ingested protein is used for muscle accretion and not metabolized and stored as fat.

The net energy (NE) system has attracted the attention of the poultry community [6, 9–11]. In theory, NE values describe more precisely than the AMEn system the energy of the ingredients for metabolic functions and therefore, NE should predict more accurately bird performance [12, 13]. However, studies on the benefits of the NE system in poultry are limited and contradictory [5, 14]. Data in this respect are shown in Table 1. The efficiency of utilization of nutrients in broilers is greater for EE (range from 84% to 90%) than for carbohydrates (range from 75% to 78%) and both greater (range from 60% to 68%) than for CP [12, 14, 15]. However, the estimated efficiency for commercial diets varies only between 73% and 76% [10]. In this particular, lipid sources should be the most benefited ingredients when the NE rather than the ME system is used [16].

Under practical conditions, most feed companies use table values, often modified by practical experience or NIRS analyses, to estimate the energy content of ingredients. Currently, predictive equations are gaining interest and used by major companies involved in animal feeding. However, factors such as physico-chemical characteristics of the diet, including heat processing (HP), feed form, and particle size, ingredient composition, and inclusion of feed additives, influence energy utilization [5, 10, 17, 18]. Consequently, feed mill managers should scrutinize the energy values of poultry ingredients obtained from tables or derived from predictive equations before implementing any change. Nutritionists should be aware of the procedures used by the research institutions for feed evaluation. For example, some tables [16, 19] utilize their own set of equations based on digestible nutrients, whereas others [20] utilize the equations proposed by the WPSA [21]. In the Premier Atlas [22] tables, most energy values are derived from TME, using

Table 1. Efficiency of Utilization of Nutrients in Poultry¹ [10].

	Production	CP	Ether extract	Carbohydrates	Diet ⁵
Schiemann et al. [15]	M ² + F ³	61	84	75	73
De Groote [12]	M + G ⁴	60	90	75	74
Carré et al. [14]	M + G	68	85	78	76

¹NE to ME ratio.
²Maintenance.
³Fattening.
⁴Growth.
⁵Assuming that 25%, 20%, and 15% of the ME of the diet was provided by CP, ether extract, and carbohydrates, respectively.

adult roosters. INRA [23] utilizes average values from different research institutes corrected with the aid of equations [24, 25] from adult roosters fed ad libitum. Broiler values are then derived taking into account differences in digestibility between bird types, especially for the lipid fraction. In other tables, such as FEDNA [26, 27], a more practical approach is used, and in many instances the values are not derived exclusively from predictive equations but from empirical and experiential information.

In vivo energy bioassays are the bases of many tables of ingredient composition but they have several problems, including cost and lack of standardization, which increases variability [17, 28]. The main objective of this review is to address practical problems encountered by the industry when using tables, predictive regression equations, and in vivo tests for the evaluation of the energy content of key ingredients, namely selected protein meals, cereals, and lipid sources.

Energy Content of Diets and Ingredients

In spite of abundant published research, a simple procedure to estimate accurately the AMEn values of feed ingredients is not available. The energy contribution of ingredients to the diet depends on numerous factors. Feed form, particle size, and heat applied during the process affect the physico-chemical characteristics of the diet and thus, energy values [29–31]. Also, diet composition, including CP [8], supplemental fat [32–34], and fiber [35] contents affect energy values [36]. Finally, the cultivar [37], antinutritional factor (ANF) content [38] growing and storage conditions of the ingredi-

ents, and the supplementation of the diet with additives, such as enzymes, organic acids, emulsifiers, mineral sources, probiotics, and prebiotics, might alter energy utilization by the bird [28, 39–41].

Tabulated Values

Energy values of the ingredients provided by recognized research institutions [16, 19–23, 26, 27, 42–47] facilitate the feed formulation process. In fact, tabulated values might be the best choice for small feed mills using conventional ingredients and with limited capacity to analyze samples in real time. However, values reported in tables are often highly variable, which creates concern. Examples on the extreme variation among published tables on the energy content of high-protein SBM and fullfat soybeans (FFSB), rapeseed meal (RSM), partially decorticated sunflower meal (SFM), and corn dried distillers grain (DDGS), are shown in Tables 2–4, respectively. Differences in AMEn (kcal/kg, as fed basis) reported are 390 for SBM, 510 for FFSB, 630 for RSM, 680 for SFM, and 760 for corn DDGS. Similarly, values reported by the same institutions for cereals (Tables 5–7) and lipid sources (Table 8) have AMEn (kcal/kg) differences of 850 for rice, 250 for corn and wheat, 340 for sorghum, 470 for barley, and more than 1,000 for selected lipid sources. In some instances, these differences might be partially justified by the chemical composition of the ingredient tested. For example, differences in moisture, CP, and ANF contents explain part of the variability reported for cereals, SFM, RSM, and SBM. Also, the experimental procedure and age of the birds (i.e., broilers vs. hens) may

Table 2. Variability in Energy Content of High Protein Soybean Meal and Fullfat Soybeans¹ (as Fed).

Institution	Year	Country	Species	High protein soybean meal				Fullfat soybeans			
				CP (%)	NDF (%)	EE (%)	AMEn (Mcal/kg)	CP (%)	NDF (%)	EE (%)	AMEn (Mcal/kg)
WPSA ^{2,3,4} [42]	1989	Europe	Rooster	47.0	9.9	1.3	2.26	36.1	11.0	18.0	3.42
NRC ^{2,3} [43]	1994	USA	Poultry	47.0	9.0	0.9	2.37	37.0	10.3	18.0	3.30
INRA [23]	2002	France	Broiler	47.2	8.9	1.5	2.32	34.8	11.0	17.9	3.35
NARO ³ [45]	2009	Japan	Poultry	47.0	11.1	1.6	2.47	36.9	7.9	18.9	3.41
Premier Atlas ⁵ [22]	2014	UK	Broiler	47.0	7.5	1.7	2.42	35.5	11.0	18.5	3.36
RPRI ^{2,3,6} [46]	2014	Russia	Poultry	47.0	12.1	1.4	2.55	35.5	11.6	17.6	3.38
CVB [16]	2016	Netherlands	Broiler	46.8	8.6	1.6	2.16	36.3	12.1	19.7	3.13
Evonik ⁷ [20]	2016	Germany	Poultry	47.5	10.7	2.1	2.34	35.6	12.6	19.6	3.28
Feedipedia ⁸ [47]	2017	France	Broiler	47.1	9.7	1.6	2.32	35.2	11.7	18.4	3.64
Rostagno et al. ^{3,9} [19]	2017	Brazil	Poultry	47.0	14.2	1.9	2.28	37.3	14.4	18.8	3.39
Fedna ¹⁰ [27]	2017	Spain	Poultry	47.0	8.8	1.7	2.32	37.0	11.3	19.2	3.42

¹Values in table correspond to average values. The number of samples analyzed for each ingredient and variable differed widely among institutions (see references enclosed).

²Estimated from CF values.

³Average of 2 soybean meals differing in CP content.

⁴Pelleted diets for fullfat soybeans. Values for roosters.

⁵AMEn of 2.35 Mcal/kg for the Brazilian meal.

⁶Average of 2 types of extruded fullfat beans.

⁷Average of the Brazil and US soybean meals.

⁸Energy of fullfat soybeans in roosters: 3.40 Mcal AMEn/kg.

⁹AMEn of toasted soybeans: 3.26 Mcal/kg.

¹⁰NDF and AMEn content correspond to USA meals.

Table 3. Variability in Energy Content of Rapeseed Meal and Partially Dehulled Sunflower Meal¹ (as Fed).

Institution	Year	Country	Species	Rapeseed meal				Dehulled sunflower meal			
				CP (%)	NDF (%)	EE (%)	AMEn (Mcal/kg)	CP (%)	NDF (%)	EE (%)	AMEn (Mcal/kg)
NRC ² [43]	1994	USA	Poultry	38.0	22.6	3.8	2.00	32.0	41.4	1.1	1.54
INRA [23]	2002	France	Broiler	33.7	28.3	2.3	1.41	33.4	35.9	1.7	1.48
NARO ³ [45]	2009	Japan	Poultry	37.3	24.0	2.9	1.74	32.0	37.1	1.2	1.59
Premier Atlas [22]	2014	UK	Broiler	33.9	22.0	3.5	1.62	33.0	33.0	1.8	1.64
RPRI ³ [46]	2014	Russia	Poultry	35.5	27.5	2.5	2.00	32.0	34.8	1.7	2.04
CVB ⁴ [16]	2016	Netherlands	Broiler	34.4	25.4	3.2	1.52	33.0	34.2	1.9	1.36
Evonik [20]	2016	Germany	Poultry	34.9	31.2	3.7	1.81	32.2	32.1	1.8	1.50
Feedipedia ⁵ [47]	2017	France	Broiler	34.0	27.6	2.4	2.04	31.7	36.7	1.8	1.87
Rostagno et al. [19]	2017	Brazil	Poultry	36.2	25.1	2.6	1.74	33.4	40.7	2.0	1.80
Fedna [27]	2017	Spain	Poultry	34.0	27.5	2.4	1.73	32.0	36.0	1.5	1.52

¹Values in table correspond to average values. The number of samples analyzed for each ingredient and variable differed widely among institutions (see references enclosed).

²NDF data from NRC [44].

³NDF data estimated from CF values.

⁴Average of 2 dehulled sunflower meals differing in CP content.

⁵Rooster values for the sunflower meal.

explain part of the differences reported for the lipid sources. However, the wide differences in energy values for all the ingredients are difficult to justify and deserves a thorough revision by the scientific community.

Predictive Regression Equations

Regression equations based on NIRS analyses are easy to implement, allow quick updates of the ingredient nutritive value, and maximize

Table 4. Variability in Energy Content of Corn DDGS¹ (as Fed).

Institution	Year	Country	Species	CP (%)	NDF (%)	EE (%)	AMEn (Mcal/kg)
WPSA [42]	1989	Europe	Rooster	25.2	—	6.8	2.43
NRC ² [43]	1994	USA	Poultry	28.5	32.5	9.0	2.93
INRA [23]	2002	France	Broiler	24.6	31.4	3.9	2.17
NARO [45]	2009	Japan	Poultry	26.2	38.0	11.0	2.90
Premier Atlas [22]	2014	UK	Broiler	27.0	38.7	9.0	>2.44
CVB [16]	2016	Netherlands	Broiler	26.5	28.8	11.5	—
Evonik [20]	2016	Germany	Poultry	26.9	37.9	10.2	2.61
Feedipedia [47]	2017	France	Broiler	26.2	30.4	9.9	2.62
Fedna [27]	2017	Spain	Poultry	26.0	26.4	10.1	2.40

¹ Values in table correspond to average values. The number of samples analyzed for each ingredient and variable differed widely among institutions (see references enclosed).

² NDF data from NRC [44].

Table 5. Variability in Energy Content of Broken (Polished) Rice¹ (as Fed).

Institution	Year	Country	Species	Moisture (%)	CP (%)	Starch (%)	EE (%)	AMEn (Mcal/kg)
NRC ² [43]	1994	USA	Poultry	11.0	8.7	75.2	0.7	2.99
INRA [23]	2002	France	Broiler	12.6	8.0	75.9	1.2	3.43
NARO [45]	2009	Japan	Poultry	14.8	7.5	—	2.7	3.28
Premier Atlas [22]	2014	UK	Broiler	11.0	7.5	71.0	1.2	3.40
RPRI [46]	2014	Russia	Poultry	12.0	8.3	48.6	1.8	2.67
CVB [16]	2016	Netherlands	Broiler	11.5	7.8	72.5	0.8	3.35
Evonik [20]	2016	Germany	Poultry	12.0	8.2	76.0	1.2	3.52
Rostagno et al. [19]	2017	Brazil	Poultry	11.6	8.3	74.9	1.2	3.22
Fedna [27]	2017	Spain	Poultry	12.8	7.5	71.8	1.2	3.43

¹ Values in table correspond to average values. The number of samples analyzed for each ingredient and variable differed widely among institutions (see references enclosed).

² Starch data from NRC [44].

Table 6. Variability in Energy Content of Corn and Soft Wheat¹ (as Fed).

Institution	Year	Country	Species	Corn					Soft wheat			
				Moisture (%)	CP (%)	Starch (%)	EE (%)	AMEn (Mcal/kg)	Moisture (%)	CP (%)	Starch (%)	AMEn (Mcal/kg)
WPSA [42]	1989	Europe	Rooster	14.0	8.6	59.9	3.9	3.25	13.0	11.3	61.9	3.07
NRC ² [43]	1994	USA	Poultry	11.0	8.5	62.6	3.8	3.35	11.0	11.5	60.0	3.12
INRA [23]	2002	France	Broiler	13.6	8.1	64.1	3.7	3.13	13.2	10.5	60.5	2.88
NARO [45]	2009	Japan	Poultry	14.5	7.6	—	3.8	3.28	11.5	12.1	—	2.97
Premier Atlas [22]	2014	UK	Broiler	13.0	8.0	63.0	3.6	3.21	13.0	11.0	60.0	3.00
RPRI [46]	2014	Russia	Poultry	13.0	8.5	61.1	4.0	3.30	12.0	11.5	54.9	2.95
CVB [16]	2016	Netherlands	Broiler	13.3	7.6	64.9	3.6	3.23	14.2	11.2	60.3	2.98
Evonik [20]	2016	Germany	Poultry	12.0	7.4	64.4	3.6	3.30	12.0	11.7	60.2	3.08
Feedipedia [47]	2017	France	Broiler	13.7	8.1	63.3	3.7	3.11	13.0	11.0	60.1	2.87
Rostagno et al. [19]	2017	Brazil	Poultry	11.1	7.9	63.4	3.8	3.36	12.5	11.5	56.7	3.04
Fedna ³ [27]	2017	Spain	Poultry	13.6	7.5	63.8	3.6	3.28	10.9	11.2	60.4	3.10

¹ Values in table correspond to average values. The number of samples analyzed for each ingredient and variable differed widely among institutions (see references enclosed).

² Starch data from NRC [44].

³ Values correspond to average of Spanish grains.

Table 7. Variability in Energy Content of Low Tannin (<0.5%) Sorghum and Barley¹ (2 Row) (as Fed).

Institution	Year	Country	Species	Sorghum					Barley			
				Moist. (%)	CP (%)	Starch (%)	EE (%)	AMEn (Mcal/kg)	Moist. (%)	CP (%)	Starch (%)	AMEn (Mcal/kg)
WPSA [42]	1989	Europe	Rooster	13.0	10.4	63.5	3.5	3.18	13.0	11.7	52.2	2.82
NRC ² [43]	1994	USA	Poultry	13.0	8.8	70.0	2.9	3.29	11.0	11.0	50.2	2.64
INRA [23]	2002	France	Broiler	13.5	9.4	64.1	2.9	3.23	13.3	10.1	52.2	2.61
NARO [45]	2009	Japan	Poultry	13.5	8.8	—	3.1	3.21	11.5	10.6	—	2.78
Premier Atlas [22]	2014	UK	Broiler	13.0	9.5	62.0	3.0	3.16	13.0	11.0	52.9	2.72
RPRI [46]	2014	Russia	Poultry	13.0	9.5	46.8	3.1	2.95	13.0	11.0	49.9	2.67
CVB [16]	2016	Netherlands	Broiler	12.8	8.7	62.5	2.8	3.05	13.3	10.0	54.0	2.66
Evonik [20]	2016	Germany	Poultry	12.0	9.2	65.0	3.4	3.25	12.0	11.2	49.7	2.70
Feedipedia ³ [47]	2017	France	Broiler	12.6	9.4	65.1	3.0	3.28	12.9	10.3	52.0	2.35
Rostagno et al. [19]	2017	Brazil	Poultry	12.9	8.8	66.6	3.3	3.20	12.9	10.8	52.1	2.70
Fedna [27]	2017	Spain	Poultry	13.0	8.9	64.2	3.0	3.26	10.1	11.3	51.9	2.78

¹Values in table correspond to average values. The number of samples analyzed for each ingredient and variable differed widely among institutions (see references enclosed).

²Starch data form NRC [44].

³AMEn of barley (2 row) in roosters was 2.75 Mcal/kg.

Table 8. Variability in Energy Content (Mcal/kg) of Selected Fat Sources¹.

Institution	Year	Country	Species	Tallow	Lard	Poultry fat	Coco oil	Palm oil	Rape oil	Soy oil
WPSA [42]	1989	Europe	Rooster	7.00	8.50	9.00	8.50	8.00	8.50	9.00
INRA [23]	2002	France	Broiler	7.22	8.25	—	8.37	7.04	9.00	9.00
Premier Atlas [22]	2014	UK	Broiler	8.13	—	7.96	9.06	6.33	9.29	8.98
CVB [16]	2016	Netherlands	Broiler	7.26	7.32	8.14	8.46	7.23	8.63	8.35
CVB [16]	2016	Netherlands	Hens	8.00	9.71	10.28	9.77	9.77	9.77	10.30
Rostagno et al. [19]	2017	Brazil	Poultry	7.40	8.08	8.68	7.92	—	8.78	8.79
Fedna [27]	2017	Spain	Poultry	7.25	8.60	8.79	8.50	8.15	8.80	9.00

¹Values in table correspond to average values. The number of samples analyzed for each ingredient and variable differed widely among institutions (see references enclosed).

the use of lab data in the feed formulation process. Online predictive equations are of primary interest in feed companies with plants located in different locations and with a high number of formulas per plant. However, the procedure is not free of problems, some of which are as follows:

- The samples used to create the predictive equation might not belong to the same population than the sample in evaluation. Even more, in many occasions the samples used are of “unknown” origin.
- Because of lack of information, the equation predicts the energy based on absolute chemical values rather than on digestible or available nutrients. Consequently, the potential variability because of processing conditions and ANF content of the ingre-

dients on energy utilization are not taken into account.

- The sum of chemical analyses data from major components (proximal analyses, NDF, starch, and sugars) of the test sample do not add to 100%.
- The analytical methods used in the determination of starch, CP, EE, and NDF are not specified, resulting in discrepancies among labs.
- Nitrogen free extract (NFE) is used as a key variable to estimate the energy value of the ingredients.
- The predictive equation used was obtained using a reduced number of samples and within a narrow range of the variables, resulting in low r² value.

The use of predictive equations obtained from a set of samples belonging to a population

different to that of the target sample is quite common and results in inaccurate estimation of the energy content. For example, in many instances the original equation used to estimate the energy value of cereal by-products from the food industry was obtained using co-products from grains processed under different conditions (i.e., wet vs. dry processes; low vs. high steam temperature). Also, a frequent mistake in the evaluation of SBM in countries which import meals from different origins (i.e., European Union-28) consists in estimating the energy content from samples collected in the previous month. The information needed, however, is not the value of the meals already used but that of the meals to arrive to the port in coming vessels.

Because of the limited information available, regression equations are often based on chemical analyses and not on digestible values. This limitation creates a problem in the evaluation of ingredients with a variable content in thermostabil ANF (i.e., SBM and RSM) or ingredients which might have been over- or under-processed (i.e., cereal DDGS and SBM).

A frequent problem in small feed mills is that the sum of major components (moisture, ash, CP, EE, NDF, sugar, and starch, as well as soluble fiber and organic acids in some cases) is not close to 100%. In the presence of inconsistencies in chemical lab analyses (values lower or higher depending on potential lab errors), the utilization of predictive equations will result in the misuse of the ingredient and in important production and/or economic losses.

In practice, one of the main problems encountered with the use of predictive equations is the lack of information on the techniques used to analyze major dietary components. The specific analyses used by the different institutions included in this review are reported in the corresponding publications and are not the subject of this paper. For example, starch values are greater when determined by polarimetry using the Ewers method (ISO 10520 [48]) than when determined using the amylase enzyme method (AOAC 996.11 method [49]). The differences reported between both methods are limited for cereals (1 or 2 percentage points) but important for ingredients such as soy products, yeasts, and lupins (Table 9) or for ingredients that have been heat-processed. For CP determination, the

Table 9. Starch Content (% as Fed) and Analytical Procedure of Selected Ingredients [16].

	Procedure		Difference	
	Ewers	Amylase	Units	%
Barley	54.0	52.8	1.2	2.3
Corn	64.9	62.0	2.9	4.7
Wheat	60.3	58.9	1.4	2.4
Sorghum	62.5	60.6	1.9	3.1
Wheat bran	16.5	13.6	2.9	21.3
Corn DDGS	4.8	2.9	1.9	65.5
Soybean meal	6.7 ¹	1.0	5.7	–
Lupins	15.0 ¹	0.8	14.2	–

¹Samples analyzed in the lab.

Dumas procedure (AOAC 990.03 method [49]) yields higher values than the Kjeldahl procedure (AOAC 2001.11 method [49]). Similarly, EE values are lower when analyzed directly (AOAC 920.39 [49]) than when analyzed after HCl hydrolysis (AOCS method Am 5.04 [50]), with more pronounced differences when the lipid is tightly bound to other constituents of the ingredient (i.e., wheat and corn DDGS) (Table 10). Finally, NDF values are lower when amylase is used [51], but higher when part of the protein of the ingredient is linked to the fiber fraction (i.e., corn DDGS). Consequently, nutritionists should insure that the originals and the test samples were analyzed following the same lab protocols. As examples, the CVB [16] tables use Kjeldahl for CP, enzymatic method for starch, and previous HCl hydrolysis for broilers (but not for layers and roosters). The WPSA [21] tables, however, use enzymatic methods for starch and petroleum or diethyl ether extraction without any previous HCl hydrolysis, for EE. The Rostagno et al. [19] tables use starch values obtained by the enzymatic method. In contrast, in the Feedipedia tables [47] most starch data were obtained by polarimetry. Moreover, the analyses procedures are not specified in many of the most commonly used tables of ingredient composition.

The use of NFE as a variable in many of the prediction equations available [21, 42] is of concern. The NFE is not a defined chemical component but calculated by difference between 1,000 and the sum (g/kg) of moisture, CP, ash, EE, and CF. Consequently, all the potential errors and mistakes associated with CP, ash, EE, and CF evaluation, including variability in lab

Table 10. Ether Extract Content (% as Fed) and Analytical Procedure of Selected Ingredients.

	Premier Atlas [22]		CVB [16]	
	EE	HCl-EE ¹	EE	HCl-EE
Corn	3.6	4.0	3.6	4.2
Wheat	1.6	2.3	1.4	1.8
Soybean meal, 47% CP	1.7	2.6	1.6	2.7
Soybean meal expeller	8.0	8.9	8.1	9.0
Fullfat soybeans	18.5	19.5	19.7	20.4
Rapeseed meal, 34% CP	2.5	3.6	3.2	4.2
Corn DDGS	10.2	11.4	11.5	13.2
Wheat DDGS	4.7	7.5	—	6.8

¹ Previous HCl hydrolysis.

determinations, affect the final energy value of the ingredient. Moreover, the NFE concept gives the same energy value to organic acids or sugars as to cellulose or lignin, resulting in poor estimation of the energy of many ingredients.

Frequently, predictive regressions are obtained with a low number of samples, and often the values are applicable only within a certain range of values. If the equation is used to evaluate samples out of the range, the predictive value will be inaccurate, especially as we move to the most extreme values. For example, equations obtained with uncooked or severely heated samples of SBM or soybeans should not be used in the evaluation of commercial samples that contains between 2 and 6 mg trypsin inhibitors (TI)/g. Consequently, it is important to verify before use, the number of samples, the interval of confidence, the range of valid values, and the residual standard deviation of the equation.

In Vivo Bioassays

In theory, in vivo trials values are best for estimating the energy content of ingredients [37, 52–54]. However, in vivo tests are time consuming and expensive, and consequently the assays are conducted with a limited number of samples, resulting in data that might not be always accurate [18]. An additional problem of the system is the disparity of results among researches, caused in many occasions by the procedure as well as the cultivar used [37]. In a recent review, Yegani and Korver [37] reported variations in AME content of wheat samples from 12 studies conducted from 1983 to 2009. In vivo values for broilers in kcal/kg varied from 2,028 to 2,874 as

reported by Mollah et al. [55], 2,193 to 3,578 as reported by Choct [56], or 2,627 to 3,798 as reported by Wiseman [57]. The range of values varied widely, not only among authors but also among cultivars within each study.

Wheat cultivar, bird type, environment, and storage conditions of the grain are factors that affect the nutrient profile and the ANF content of the wheat, and thus its AME value [58–60]. Black et al. [58] conducted a study with 40 samples of different wheat cultivars in broilers and laying hens. In this study, the AME content (kcal/kg DM) of the wheat varied from 2,915 to 3,728 in layers and from 2,844 to 3,657 in broilers. The detrimental effect of new season wheats on energy digestibility has been reported in many studies. Choct and Hughes [61] reported that after 3 mo of storage, the AMEn of Australian wheats varied from no effects to 715 extra kcal/kg DM, depending on the variety. Also, Yegani and Korver [37] reported that the AME of wheat samples for poultry increased from 2,194 to 2,873 kcal/kg after 1 yr storage. Consequently, the energy content of a wheat might vary depending on time elapsed from harvest. The information available suggests that in vivo data obtained in research facilities, in which the type of bird and origin of the wheat is not specified, should be used with caution.

Factors Affecting the Energy Content of Diets and Ingredients

Factors related to the bird, the methodology used in the estimation, and the physico-chemical characteristics of diets and ingredients affect energy utilization by the bird.

Table 11. Energy Content (Mcal/kg as Fed) of Key Ingredients According to Type of Poultry.

	CVB [16]			Feedipedia [47]		Rostagno et al. [19]	
	Broiler	Rooster	Layer	Broiler	Rooster	Poultry	Layers
Corn	3.23	3.27	3.32	3.11	3.18	3.36	3.39
Sorghum	3.05	3.17	3.20	3.28	3.34	3.20	3.23
Wheat	2.98	3.06	3.07	2.87	2.99	3.04	3.08
Barley	2.66	2.85	2.86	2.35	2.75	2.70	–
Soybean meal, 47% CP	2.16	2.20	2.21	2.32	2.36	2.28	2.44
Soybean meal expeller ¹	2.47	2.53	2.62	2.32	–	2.19	2.27
Fullfat soybeans, toasted	3.13	3.32	3.55	3.64	3.40	3.39	3.31
Rapeseed meal, 34% CP	1.52	1.74	1.76	2.04	1.57	1.74	1.85
Sunflower meal, 32% CP ²	1.38	1.47	1.49	–	1.87	1.80	1.90
Corn DDGS, 28% CP	–	–	–	2.61	2.62	–	–

¹ Average of soybean meal 44% CP and 45% CP.
² Average of sunflower meal 30.8% CP and 35.2% CP.

Table 12. Energy Content (Mcal AMEn/kg) of Soybean Meal and Fullfat Soybeans for Poultry [16].

Soy product	Broiler	Rooster	Layer
Soybean meal 48.5% CP	2.24	2.23	2.23
Soybean meal 46.8% CP	2.16	2.20	2.21
Soybean meal 42.6% CP	2.01	2.08	2.09
Soybean meal expeller 43.8% CP	2.47	2.53	2.62
Fullfat soybean, toasted 36.3% CP	3.13	3.32	3.55

Bird Effects

The energy content of diets and ingredients varies with type and age (i.e., pullets vs. chicks vs. layers vs. turkeys), the genetic background, and the health status of the birds [6, 37, 60]. In general, adult birds extract more energy from raw materials than young birds, with more pronounced differences for ingredients difficult to digest, such as high fiber materials and saturated fats [58, 62]. Many of the available tables provide different energy values for young broilers and adult birds [16, 19, 22, 23, 47]. Other tables, however, do not differentiate by age [20, 43, 45, 46]. Moreover, in practice, not many feed mills use different energy values for poultry according to age. Even more, studies comparing the energy content of a given ingredient among avian species, poultry breeds, and bird age are not easy to find for many local ingredients (i.e., cereal by-products, native legumes, and commercial lipid mixtures). Tables 11–13 offer comparative energy values of key ingredients (cereals and protein meals, soybean products, and lipid sources, respectively) according to age and type of bird [16, 19, 47]. There is a high variability in energy

Table 13. Energy Content (Mcal/kg) of Selected Lipid Sources According to the Age of the Birds [16].

	C18:2 (%)	Broiler	Rooster	Layer
Coconut oil	2.0	8.46	8.50	9.77
Palm oil	11.1	7.23	8.50	9.77
Rapeseed oil	22.3	8.63	8.50	9.77
Soybean oil	54.1	8.35	8.96	10.30
Linseed oil	16.1	8.49	8.50	9.77
Tallow	4.9	7.26	6.96	8.00
Animal fat	9.0	7.44	8.48	9.75
Lard	10.5	7.32	8.44	9.71
Poultry fat	36.5	8.14	8.94	10.28
Fish oil	1.6	8.10	–	–

value among tables, with some of the differences reported not easily justified by those variables, exclusively.

Physico-Chemical Characteristics of Diets and Ingredients

Processing, physical characteristics, and ingredient composition of the diet affect the proportion of the gross energy (GE) utilized by the bird. In this respect, HP, feed form (mash vs. pellets), and particle size of the ingredient (fine vs. coarse grinding) are the most relevant factors [63–66]. Also, CP, fat, and fiber content, presence of ANF, and the inclusion of additives, such as enzymes and emulsifying agents, are factors to consider [38, 67, 68].

Heat Processing Heat processing of cereals at temperatures above 100°C is a common practice to increase nutrient digestibility and growth performance in piglets [69, 70–72]. However, the information available on its effects on

gastrointestinal tract (GIT) function and nutrient utilization is contradictory in poultry, with some researches showing improvement [73], no effect [74], or even negative effects [65, 75]. Heat processing, including the pressure applied, disrupts the structure of the cell walls, releasing the lipids contained in the oil bodies of certain ingredients such as soybeans [76] or increasing the availability of the starch of other ingredients such as peas [77], thereby increasing energy utilization. On the other hand, an excess of heat might reduce the energy and nutritive value of grains because of starch retrogradation, especially of those cereals such as rice that has a high starch digestibility in the natural state [78]. Also, HP increases digesta viscosity of cereals with a high non-starch polysaccharide (NSP) content, which in turn might reduce nutrient digestibility [74]. Moreover, the improvement in energy utilization reported with HP of cereals and certain legumes by some authors tended to disappear with age [59, 74, 77].

Feed Form and Particle Size Feed form influences broiler performance, with birds fed pellets or crumbles being more efficient and growing more rapidly than birds fed mash. The pelleting process consists of grinding the ingredients to reduce particle size, mixing the ingredients, conditioning of the mixture by using steam at high temperature (120–130°C) for a short time, and the passing of the conditioned meal through the press, which results in a further decrease in particle size. The hot pellets are then cooled and stored. The process affects not only feed intake but also GIT development, resulting in changes in nutrient utilization and microbial growth and profile [79, 80]. Consequently, the effects of pelleting on nutrient digestibility and energy content of the diet are inconsistent, with a final response that depends on factors such as heat applied, particle size, and ingredient composition of the diet. These effects might be additive or counteract each other [81, 82], resulting in a variable final impact. For example, cell wall breakage, a result of the physical stress of fine grinding and the pressure applied during the process, may facilitate the accessibility of enzymes to the encapsulated nutrients [81]. In addition, starch digestibility depends not only on the structure of the glucose chains, but also on the characteristics of the protein/lipid matrix

protecting the starch granules from degradation. In this respect, more pronounced benefits of fine grinding are expected for ingredients with highly protected starch, such as peas and hard wheat, than for ingredients with less protected starch such as rice [37, 83, 84]. In fact, the correlation between starch digestibility and wheat hardness tends to be negative [85]. Finally, pelleting might release the lipids contained in the oil bodies of ingredients such as toasted soybeans and corn, increasing energy utilization [21, 65, 86]. In this respect, the WPSA [21] recommends different energy values for a given sample of FFSB depending on feed form.

Recent research has shown that the beneficial effect of pelleting on feed efficiency reflects a reduction in feed wastage and not necessarily a better utilization of the nutrients [81, 82, 87]. In fact, when diets are based on raw materials with a high content of NSP (i.e., β -glucans and xylans) such as rye, wheat, triticale, and barley, pelleting at high temperatures might solubilize the NSP fraction, increasing digesta viscosity and reducing nutrient digestibility. The negative effects of over-heating ingredients with a high content of NSP are more pronounced for the lipid fraction [88, 89], but the effects are less apparent or even disappear when an adequate exogenous enzyme complex is included in the diet.

Feed form and particle size of the diet affect the development and function of the GIT, especially of the gizzard, modifying digesta potential of hydrogen, energy utilization, and broiler growth [86]. In addition, pellet feeding and fine grinding of ingredients increase the rate of passage of the digesta through the GIT resulting in greater feed intake, which in turn might alter the microbiota profile and energy content of the feed [35, 90, 91]. When the diet is pelleted, feed ingredients are ground usually fine to improve pellet quality, as a result pelleting and particle size effects are often confounded.

A poorly developed gizzard, as occurs in broilers fed pellets or finely ground diets, increases proventriculus and gizzard potential of hydrogen and might reduce the intensity of the antiperistaltic movements, decreasing energy digestibility [82, 92]. The physical characteristics of the diet affect the energy content of feeds by improving GIT function when diets are ground coarse or by facilitating the contact of nutrients

and enzymes when ground fine. Also, the microbial profile might be altered by the physical structure of the digesta, affecting energy utilization. Consequently, all these factors often counteract each other with final effects that might depend on other factors, such as health status of the bird [35]. Probably, the main benefit of pelleting consists in a reduction in feed wastage and an increase in voluntary feed intake, which results in improved growth with limited effect on nutrient digestibility [84, 93, 94].

Ingredient and Chemical Composition of the Diet

One of the main assumptions of the AME system is that the energy content of the ingredients are additive. However, dietary energy depends to a high extent on the interaction between the feed and the bird and the assumption might not be always correct. For example, level and type of fiber, fat content of the diet, presence of ANF, contaminants, and toxins, and the use of enzymes (phytases, carbohydrases, and proteases), emulsifiers, organic acids, and other additives modify the energy contribution of the ingredients to the diet.

Fiber Content The influence of fiber content of the diet on voluntary feed intake and nutrient digestibility in poultry is a subject of debate [41, 95]. Dietary fiber has been considered as an ANF factor with negative effects on palatability, feed intake, and nutrient digestibility [96]. However, numerous reports [68, 97–100] have shown that the inclusion of moderate amounts (2%–3%) of insoluble fiber sources in diets low in fiber improves gizzard function, nutrient digestibility, and growth, especially in young broilers and pullets [35, 101, 102]. In fact, little benefits on nutrient digestibility and energy content of feeds were observed with the inclusion of extra amounts of fiber in laying hen diets [103, 104]. Similarly, little or even negative effects on energy utilization and feed intake are expected with the use of soluble fiber sources [35, 100, 105]. Consequently, the final contribution of fiber to dietary energy will depend not only on the amount and type of fiber used but also on the age of the target bird.

Fat Content Fat supplementation reduces the rate of passage of the digesta through the GIT

which favors the utilization of the lipid, carbohydrate, and protein fractions of the diet [32, 33, 62, 106]. Unsaturated monoglycerides improve micelle formation and the absorption of the saturated fat present in other ingredients of the diet, contributing to the “so called” extra caloric effects of supplemental fat [107]. Consequently, the energy content of the diet might increase more than expected when supplemental, unsaturated fat is used.

Antinutritional Factors and Supplementation of Additive The presence of ANF affects nutrient utilization and energy content in many ingredients. In practice, the role of TI in SBM and peas, glucosinolates in RSM, tannins in sorghum, non-digestible oligosaccharides in legumes, xylans and β -glucans in small grains, and phytate in all seeds should be understood and controlled under practical conditions. In general, the presence of ANF affects not only the energy content of the ingredient “per se” but also can damage the integrity of the mucosa affecting GIT function and utilization of the energy of other constituents of the diet. The use of adequate technologies (i.e., HP of SBM for TI reduction and enzymes supplementation to decrease NSP and phytates in grains and legume seeds) might solve most of the problems caused by these ANF.

Additives (i.e., exogenous enzymes, organic acids, probiotics, prebiotics, emulsifiers, and essential oils) are commonly used in diets for young chicks without in-feed antibiotics [41]. The benefits of enzymes (or other additives) on energy content of ingredients have been well documented [89, 108–110]. However, the real contribution of additives to diet energy is difficult to quantify. In many instances, matrices that include “energy equivalent values” are used to account for the potential benefit of the additive on energy utilization, facilitating its implementation in diet formulation. However, when a combination of several additives, each of them with its own energy matrix, is incorporated in the diet, the “matrix approach” will result in over-estimation of the potential benefits of the combination of additives. This occurs because there is a finite amount of energy to be made digestible and a full additive effect of all the individual additives on energy is rarely obtained.

Energy Evaluation of Ingredients

Protein Sources SBM, RSM, SFM, and corn DDGS are the main plant protein sources used worldwide in poultry feeds. These ingredients are important sources of AA, but their energy content is of increased interest in feed formulation.

Because of its protein quality and nutritive value, SBM is the protein source of choice in poultry diets [111]. The energy content of high-protein SBM (47% CP), as recommended by the different research institutions, ranges from 2.16 to 2.55 Mcal/kg [16, 46], differences that are difficult to explain due to differences in EE and CP contents, exclusively (Table 2). The conditions applied during the crushing and oil extraction processes, posterior soy hulls inclusion, and country of origin of the beans affect the energy content of the SBM [112–114]. Under-heating reduces the quality of the protein of the final product because of the presence of excessive amount of TI and consequently, its energy content. On the other hand, over-heating reduces the concentration of TI but at the same time increases the incidence of Maillard reactions, which reduces the energy the bird can utilize. Consequently, to maximize energy content, a high reduction of TI together with a low incidence of Maillard reactions are required. In addition, the variability in sucrose and oligosaccharide content [38, 52, 53] might explain differences in AMEn among SBM samples [38]. However, none of the predictive equations available uses any of these variables in energy evaluation of SBM.

An example of the advantages and disadvantages of the predictive regression equations available for the evaluation of the energy content of SBM is that of the WPSA equation [21]. The equation [$\text{AMEn (Mcal/kg DM)} = 3.75 \times \text{CP} + 7.05 \times \text{EE} + 1.49 \times \text{NFE}$] is widely used and recognized as a good tool to evaluate the energy content of SBM in poultry [20]. However, this equation, published 32 yr ago, might not be as precise as currently required. For example, the same equation is recommended for all SBM, independent of processing conditions, sugar content, and origin of the beans. Consequently, the equation does not penalize the energy content of SBM produced in crushing plants in which the

heat treatment applied during the oil extraction process is not adequate or in those meals with a reduced sugar content [38, 94].

A second problem of the WPSA [21] equation is the coefficient applied to the EE fraction. SBM contains usually 1.5%–1.8% EE [38], although higher values are often reported [19, 53]. High-EE contents mean that some extra oil was left in the meal after the extraction process or, more probably, that the by-products of the oil refining (i.e., gums and acid soapstocks) or soy protein concentrate (i.e., soy molasses) industries were added to the meal. In addition, EE values vary with the procedure used, with up to 1% higher values with the use of HCl hydrolysis. Consequently, the energy provided by the lipid fraction of the SBM might differ among SBM samples even when they have similar CP and theoretical EE contents.

A last concern with the WPSA [21] equation is the use of NFE as a main variable in the estimation of energy content. The NFE fraction does not have a clear nutritional meaning. It is obtained by difference between 1,000 and the proximal analyses contents in g/kg. Therefore, the use of NFE for energy prediction includes 2 potential problems: (a) no distinction among SBM components, giving the same energy value to lignin, pectin substances, or more digestible components such as sucrose, and (b) all mistakes that might occur during the calculation process, including faulty lab analyses, will affect energy estimation. As a result, NFE should not be included in predictive regression equations to estimate the energy content of any ingredient.

Intuitively, a sound equation for estimation of the AMEn of an SBM batch should include, as main variables, digestible protein rather than CP content (practical lab methods for its determination not available yet) and the amount of sucrose (easy to analyze). Also of interest could be the inclusion in the equation of the real fat content and the presence of oligosaccharides (stachyose, verbascose, and raffinose; approximately 7% of the meal on DM basis). Oligosaccharides are not digested in the GIT, acting as ANF and reducing the nutritional value of the meal [115]. However, oligosaccharides are fermented easily in the large intestine and when present in small proportions, they might yield valuable energy in old birds [38, 116].

Table 14. Protein Quality, Sugar, and Oligosaccharide Content of SBM According to the Country of Origin of the Beans¹ ([38]).

	SBM origin			SEM	P-value
	Argentina	Brazil	USA		
n	170	165	180		
Lys, % CP	6.10 ^b	6.07 ^c	6.17 ^a	0.005	***
TIA, ² mg/g	2.6 ^b	2.7 ^b	3.5 ^a	0.08	***
PDI, ³ %	16.0 ^b	15.0 ^c	19.5 ^a	0.40	***
KOH solubility, %	81.2 ^a	82.0 ^b	86.1 ^a	0.23	***
HDI, ⁴ A. Red	12.5 ^b	15.6 ^a	9.0 ^c	0.37	***
Sucrose, %	7.8 ^b	6.4 ^c	8.4 ^a	0.81	***
Stachyose, %	5.7 ^b	5.3 ^c	6.4 ^a	0.44	***
Raffinose, %	1.4 ^b	1.6 ^a	1.1 ^c	0.23	***

a,b,c Within a row, means without a common superscript differ significantly. *** P < 0.001.

¹Urease < 0.03 mg N/g for all origins (P < 0.01).

²Trypsin inhibitor activity.

³Protein dispersability index.

⁴Heat damage indicator [117]. Values varied from 0 (low damage of CP) to 40 (high damage of CP).

The chemical composition, and therefore the energy content of the SBM, varies with the country of origin of the beans, an effect related probably with day length (latitude), light, soil characteristics, and growing, harvesting, and storage conditions of the beans [76]. As an average, the CP content of the SBM is lower for the Argentina meals than for the USA or Brazil meals [52, 53], suggesting that the AMEn should be lower in samples from Argentina. Garcia-Rebollar et al. [38] conducted an 8-yr survey with SBM samples (n = 515) processed in the country of origin of the beans. In this report, the USA meals had higher TI, potassium hydroxide, and protein dispersability index values but lower heat damage indicator [117] than the Brazil SBM, suggesting a higher digestibility and greater energy content of the protein fraction of the USA meals (Table 14). Also, the USA meals had less fiber and more soluble sugars than the Brazil meals, with SBM from Argentina being intermediate, suggesting differences in energy utilization by the bird [38, 113]. In fact, the energy content of the SBM, using the predictive equation recommended by the WPSA [42], was of 2,621, 2,605, and 2,576 kcal/kg DM for the USA, Brazil, and Argentina meals, respectively [38]. For FFSB, the energy values reported by the different institutions are extremely variable (Table 2) with part of the differences accounted by the chemical composition of the original beans (i.e., moisture, lipid, and sucrose content) and the type of processing (i.e., wet extrusion vs. toasting). In all

cases, the wide range of values reported (3.13–3.64 Mcal/kg) between the CVB [16] and Feedipedia [47] are difficult to justify.

Similar or even greater variability in energy values to those of SBM and FFSB has been reported for RSM, SFM and corn DDGS (Tables 3 and 4, respectively). Energy values provided by the different research institutions for RSM varied from 1.41 to 2.04 Mcal/kg [23, 47], a difference difficult to explain exclusively, by the processing conditions or the glucosinolate content of the meals. The glucosinolates present in the RSM reduce feed intake, protein digestibility, and energy content proportionally to its level in the diet. However, traders do not report in most instances the glucosinolate content of commercial RSM. On the other hand, differences in energy for RSM of different origins, such as canola meal (RSM with high CP and low glucosinolate content produced in Canada), regular RSM produced in Europe, and Indian RSM (often a mixture of rape and mustard meals) are expected. For SFM, the primary concern is the lack of uniformity among batches. The main reason for the variability is the amount of hulls added to the meal after oil extraction. As indicated for previous ingredients, the wide variability range (1.36–2.04 Mcal/kg on as fed basis) reported among sources of information [16, 46] for meals with similar CP content are difficult to justify. For corn DDGS, the main concerns are the amount of fat and starch remaining in the final co-product and the technique used in the lab for their determination

(i.e., HCl hydrolysis and solvent type used for lipid content). In addition, new processes used by the ethanol industry result in a reduction of these 2 components in commercial DDGS. Consequently, EE and starch content should be analyzed in samples from new suppliers for estimation of its energy content.

Cereals

Cereals are the main energy sources in commercial poultry diets worldwide. Consequently, the accurate determination of its energy content is of paramount interest. The energy content of the cereals depends on the moisture and the proportion and physico-chemical characteristics of the starch and fiber fractions (closely and negatively related) as well as on the concentration of viscous carbohydrates. A higher variability in energy is expected for wheat, barley, rye, triticale, and oats than for corn, especially in those countries in which the small grains are produced in non-irrigated lands. There is a linear positive correlation between NSP and energy content of the cereals [6]. The highest AMEn among cereals corresponds to broken rice, followed by corn, sorghum, wheat, and barley with the lowest value observed for oats (Tables 5–7). Rice had the lowest NSP and the highest starch content among cereals. In addition, rice starch is easily digested because of the small size of the granules and the weak matrix protecting the starch within the grain. Data on the AMEn content of broken rice, according to the different research institutions are shown in Table 5. The wide range reported from 2.67 Mcal/kg [46] to 3.52 Mcal/kg [20] emphasizes the need of a better evaluation of the energy content of this cereal.

Data on the energy content of the corn, according to the different institutions, are shown in Table 6. Values range from 3.11 and 3.13 Mcal/kg for Feedipedia [47] and INRA [23] to 3.35 and 3.36 Mcal/kg for NRC [43] and Rostagno et al. [19], respectively. Moisture content is probably the main constituent affecting the AMEn content of corn, although differences in energy are still evident when presenting the data on DM basis. In practice, the moisture content of the grain is not always taken into consideration when estimating the energy content of corn. Moreover, moisture content is not always ana-

lyzed correctly. For example, the use of coffee grinders, a common practice in many small feed mills, generates heat and depending on the time and energy dedicated to the grinding process, moisture will change, affecting the estimated energy value of the grain. Also, the samples are not always analyzed immediately after arrival of the truck to the feed mill but kept under uncontrolled conditions in the lab, with loss of moisture during storage, especially under hot summer conditions. The percentage of broken grains affects also the energy content of the corn. Dale [118] reported that the AMEn content of the broken grain fraction was 86 kcal/kg lower than that of the whole grain fraction. Finally, the variability in lipid content of the corn is wide, with samples produced in the Black sea region showing often EE contents below 3.0% (personal observation).

The AMEn content of sorghum varied from 2.95 Mcal/kg for RPRI [46] to 3.29 Mcal/kg for NRC [43]. The main factors affecting energy of this grain are the moisture and tannin content and the kafirin proportion of the protein fraction [119]. In the current review, all values reported correspond to low tannin grains (<0.5 mg/kg) with similar moisture content and consequently, differences reported by the research institutions for commercial batches of sorghum might not be justified.

The AMEn content (as fed basis) for wheat, reported in tables by the different institutions ranges from 2.87 Mcal/kg for Feedipedia [47] to 3.12 Mcal/kg for NRC [43], whereas for barley the values range from 2.35 Mcal/kg [47] to 2.82 Mcal/kg for WPSA [42]. These values are more variable than those reported for corn probably because of differences in starch and ANF content, especially in small grains produced in poor, dried, and non-irrigated soils. Under dry conditions, the proportion of moisture, protein, and starch (and fiber), and ANF (mainly β -glucans and xylans) content of wheat and barley depend on the cultivar used as well as on the climatic conditions during the growing season [59]. Fortunately, the inclusion of enzyme complexes overcomes the viscosity problem created by the NSP content of the diets. Probably, tables on ingredient composition should include information on the expected increase in energy content of the wheat and other cereals such as barley, rye, and oats with adequate use of enzymes. In

this respect, Fedna [27] recommends increases in the energy content of wheat, barley, and other small cereals between 1% and 4%, depending on the type and quality of the grains and the age of the bird.

Lipid Sources Fats and oils supplementation increases energy concentration, improved feed efficiency, and reduced dustiness in poultry diets [120–122]. The main factors affecting the energy content of oils and fats are the chemical quality (including GE, moisture, impurity, unsaponifiable contents, and peroxide values) and the characteristics and structure of the molecule, namely the proportion of free fatty acids, degree of unsaturation, and length of the carbon chains.

Fats are the most difficult ingredients to evaluate *in vivo* [54, 123–125]. Initially, the response to added fat was measured using simple linear models, often at a single level, estimating the energy content of the fat by difference between the energy of the control diet and that of the fat-supplemented diet. This methodology created considerable uncertainties and often resulted in values for the test fat beyond its GE value. In addition, in the determination of the energy content of a lipid source, the amount of fat included in the experimental diet is quite limited (usually less than 6% to 8%), and therefore any small mistake in lab determinations is magnified, resulting in wide confidence intervals for the estimated AME value. A multilevel approach allows a better assessment of the AME content of commercial fats [126]. However, the multilevel approach is onerous and requires extra work, which limits its use under most commercial practices.

The AME of the experimental fats is often greater when determined by difference between the AME of the control and the supplemental fat diets than when calculated from the GE and the digestibility of the supplemental fat, suggesting that fat improved the utilization of other dietary components [54, 124, 127, 128]. In fact, the energy values of fat sources using this approach are in numerous occasions [16, 54, 129, 130], higher than the corresponding GE values, a finding that does not have any biological sense. Consequently, these extremely high values are caused either by methodological problems or by the beneficial effects of supplemental fat on the utilization of the non-fiber components of the

diet [32, 106, 131]. In this respect, supplemental fat reduced rate of feed passage, facilitating the contact between nutrients and digestive enzymes, thereby increasing the utilization of other dietary components [34]. However, because of the methodology used for the calculation of the AME of the fat source, the improvement is attributed to the supplemental fat.

A concern with the use of *in vivo* test to evaluate the energy content of lipid sources is the composition of the control diet. When the basal diet does not add any supplemental fat, most of the EE is provided by the corn or other dietary ingredients, and therefore a high proportion of the lipid is entrapped within the cell structure, which is less accessible to enzyme activity, especially when the diets are fed in mash form. In contrast, in diets supplemented with extra amounts of fat, most of the EE is supplied by the lipid source, which is freely available and of easy access for lipase activity [62, 128]. Consequently, EE digestibility is expected to be lower for the control diet than for the fat-supplemented diets. All this information indicates the need of new approaches to better estimate in practice the energy content of fat sources in poultry diets.

CONCLUSIONS AND APPLICATIONS

1. The main assumption in the determination of the energy value of poultry diets is the additivity of the energy contents of the ingredients. This assumption might not be correct, especially when extra amounts of fiber, lipid sources, and enzymes are included in the diet.
2. Use of N correction to estimate the AME content of an ingredient in modern broiler and laying hen diets might penalize the real contribution of protein sources to the energy in the diet more than it penalizes that of the energy sources.
3. Table values and predictive equations are useful alternatives to evaluate in practice the energy content of the ingredients. However, to avoid misuses, both approaches require a fine scrutiny by nutritionists and feed mill managers.
4. The use of predictive equations based on analytical values obtained by NIRS analyses

looks promising as a tool to estimate the energy content of ingredients and diets.

5. In vivo bioassays, although of clear value and interest, especially for non-conventional ingredients, might not be applicable in practice to evaluate the energy content of more traditional ingredients.
6. Nutritionists and feed mill managers should use their own experience and reasoning to evaluate the pros and cons of each of the methods available to estimate the energy content of ingredients and diets. Without “good thinking”, none of the available methodologies will give accurate estimates under practical conditions.

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